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SOLAR COOLING FOR ENERGY SAVING. *CAN WE AFFORD NOT TO USE THE HEAT OF THE SUN?*

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Abstract: *Within the building sector solar cooling systems could offer economic alternatives to air conditioning. Such a system has been evaluated for moderate climatic conditions such as those existing in Braşov, Romania. The unbalanced heating and cooling loads require a back-up system and supplementary investments. The high initial cost of such absorption systems is a serious obstacle for a large scale implementation and technical solutions have to be found for less expensive systems.*

Key words: *solar cooling, absorption, case studies.*

1. Introduction

The need for a heating and cooling supply based on renewable energy has become more and more apparent. In a few decades, oil and gas will be too precious to be wasted for low temperature applications, which could be easily supplied by solar thermal. The clear and unmistakable signs of global warming highlight the urgency to reduce greenhouse gas emissions.

A growing number of demonstration projects show the huge potential for solar assisted cooling. Solar chillers use thermal energy to produce cold and/or dehumidified air. When backed up by biomass boilers, 100% renewable cooling systems are possible. Solar cooling is on the edge of wide market introduction and substantial cost reductions are expected in the next few years, through technological development and economies of scale. A typical solar cooling system also provides space heating and hot water - which is why they are often called Solar Combi+ systems. For hot water, the demand is relatively stable throughout the year and can be covered completely by solar energy. The demand for space heating is higher in winter when solar energy is less available. Ordinary solar thermal systems cover only a part of the space heating demand, with the remainder covered by a back-up system [6].

Cooling demand in summer typically correlates with high solar irradiation (Figure 1). Then, solar energy can easily provide more than half of the energy required for cooling, the remainder being provided by the same back-up system used in winter for heating. This will be a key answer to the problems created by the growth of cooling demand in many European countries [6].

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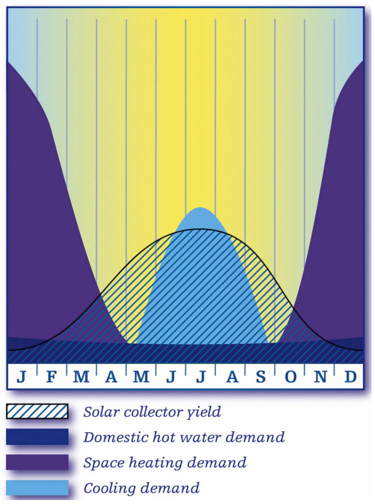

Fig. 1. *Solar cooling& heating system: demand and supply* [6]

The architectural trend to greater glass surfaces and growing comfort demand, has resulted in an increase in energy consumption for air conditioning. In some countries this has already led to an electrical grid overload and break down. This threat and the need to reduce green house gases for electricity production make the introduction of cooling with renewable energy sources indispensable.

Towards the end of last century it was considered that solar cooling would only be profitable through photovoltaic driven compression cooling machines. Optimized collectors, the improvement of other components and an enhanced system design have resulted in solar thermal cooling emerging as a real technical alternative. It is now on the verge of financially competing with systems operating with conventional electricity sources [6].

2. Short History of Refrigeration

The first known artificial refrigeration was demonstrated by William Cullen at the University of Glasgow in 1748. Between 1805, when Oliver Evans designed the first refrigeration machine that used vapor instead of liquid, and 1902 when Willis Haviland Carrier demonstrated the first air conditioner, many teams of inventors contributed with many small advances in cooling machinery. In home applications, refrigeration became a reality in 1834 with the invention of the cooling compression system by the American inventor Jacob Perkins [2].

In 1878, A. Mouchot and his assistant Abel Pifre displayed Mouchot's engine at the Universal Exhibition in Paris, and won a Gold Medal for his works, most notably the production of ice using concentrated solar heat [5].

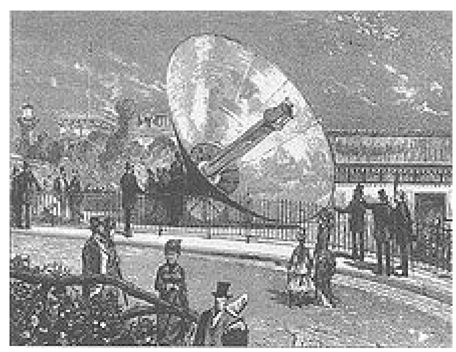

Fig. 2. *Solar generator 1878* [5]

The use of solar energy for cooling offers the advantage of energy availability that is correlated, to some degree, to the demand for cooling. Currently, the most commonly applied method uses a solar collector field to produce a hot fluid, which is used to drive a thermal chiller.

3. Technology Overview of Absorption Cooling

Absorption cooling is a mature technology with the first machine developed in 1859 by Ferdinand Carré. For the closed cycle-process, a binary working fluid, consisting of a refrigerant and an absorbent, is necessary. Carré used as the working fluid ammonia/water (NH_3/H_2O). In 1945, the company Carrier Corp, US, developed and introduced the first large commercial single-effect absorption cooling machine, ACM, using water and lithium bromide H_2O/LiBr with a cooling power of 523 kW [2]. In 1964, the company Kawasaki Heavy Industry Co, Japan produced the first double-effect, DE, H_2O/LiBr ACM. The DE ACM is equipped with a second generator and condenser to increase the overall coefficient of performance (COP) by reusing the high temperature input heat for the lower temperature generator [2]. Absorption chillers today are available in a range of 10 to 20,000 kW. In the past few years, some new developments were made in the small and medium-scale cooling range of 5 to 50 kW for H_2O/LiBr and NH_3/H_2O absorption chillers, respectively.

While absorption cooling has been common for decades, heat pump applications have only become relevant in recent years, due to the improvement in the performance figures; small gas-driven absorption heat pumps achieve COPs of approximately 1.5, i.e. using 1 kWh of the primary energy of gas (not electricity), 1.5 kWh of heat can be produced using environmental energy, which is better than the condensing boilers presently available on the market with maximum COPs of about 1.0 [2].

4. History of Solar Cooling with Absorption Chillers

In the 1970s, Arkla Industries Inc, US developed the first commercial, indirectly driven, single-effect H_2O/LiBr ACM for solar cooling with two different nominal cooling capacities. The driving heat temperatures were in the range of 90 °C and the cooling-water temperature was 29 °C, for 7 °C chilled-water temperature. The machine was installed in more than 100 demonstration projects across the US. Arkla and also Carrier Corp then developed a small-size single-effect H_2O/LiBr ACM that could work with air cooling. There was no market success mainly due to the high investment costs for solar cooling. Carrier Corp further decreased the driving temperature of a water-cooled single-effect H_2O/LiBr ACM by using a falling film generator with a large surface area. The driving heat temperature was 82 °C and the cooling water temperature was 28 °C for 7 °C cold water temperature. The production of these ACMs was stopped and the technology's licence was given to the Japanese company Yazaki. Up to the beginning of the 1990s, the company offered H_2O/LiBr ACMs with 5-10 kW cooling power (such as the WFC-600 with 7 kW) which were used for solar cooling projects. However, due to low demand, the production stopped [2].

At the beginning of the 1980s, Arkla developed a double-effect H_2O/LiBr ACM in which the lower temperature generator was supplied with solar energy, while in fossil mode the double-effect generator was fired using the higher COP. Due to the lack of demand on the market for solar cooling, the production of this cooling machine stopped and the technology was also licensed to the Japanese company Yazaki. They sold the machines for several years, but they are no longer available today. In the medium-sized performance range, the most project experiences for solar cooling exist for the single-effect H_2O/LiBr ACM WFC-10 from Yazaki, Japan, with a cooling power range of 35–46 kW. The system is generally rated as dependable and unproblematic [2].

After the market failure of low-power systems some decades ago, there has been an increased interest in low-power absorption chillers during the past decade. A range of manufacturers - including many from Europe - now offer single-effect thermal chillers with cooling power below 10 kW. The Swedish company ClimateWell alone installed several hundred units in Spain over the past two years, while in 2007 the total number of solar cooling systems was estimated at only 200 [2].

There are no general rules yet for the dimensioning of solar cooling systems and planners often do not have adequate tools to determine the energy yield and solar fraction [2].

5. Examples of Solar Cooling with Absorption Chillers

A number of demonstration projects have been launched to gain more experience in the design and operation of solar refrigeration and air-conditioning.

Up till 2007 there were 81 installed large scale solar cooling systems, SCS, including systems which are currently not in operation: 73 installations are located in Europe, 7 in Asia, China in particular, and one in America (Mexico). 60% of these installations are dedicated to office buildings, 10% to factories, 15% to laboratories and education centers, 6% to hotels and the left percentage to buildings with different final use (hospitals, canteen, sport center etc.) [3].

The overall cooling capacity of the solar thermally driven chillers amounts to 9 MW; 31% of it is installed in Spain, 18% in Germany and 12% in Greece [3]. And by 2008 there were about 100 large systems. As we see this market is on spectacular growing, so why we don't use?

Some relevant studies, systems and simulation projects will now be presented.

5.1. Greece

A study concerning the possibility of using solar energy for cooling by means of an absorption system was developed in Greece for the General Hospital of Sitia shown in Figure 3.

TRNSYS software was used to simulate the requirements of one of the constituting buildings (Figure 4) and the necessary area of solar collectors. A cooling power of 121 kW resulted being greater than the heating power, 87 kW. Different solar fractions have been considered and finally an optimal issue supported by financial and environmental benefits was adopted:

- cooling solar fraction 74.23%
- heating solar fraction 70.78%.

Fig. 3. *General Hospital of Sitia* [3]

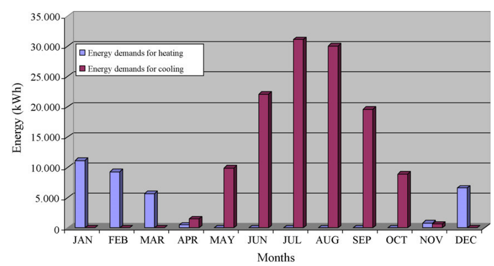

Fig. 4. *Energy demand for cooling and heating* [3]

179 solar collectors covering a surface of 500 m^2 provide the thermal energy for the 70 kW $H_2O/LiBr$ absorption chiller. A complementary 50 kW compression chiller was provided for the case of insufficient cooling conditions. The highest environmental benefits have been considered but for the secure operation of the system an auxiliary fossil fuel pre-heater of 87 kW has also been included. The investment cost without funding subsidies was 174.000 € with a payback time of 11.5 years. For a

40% funding the investment cost decreases at 104.400 € and the payback period became 6.9 years. It can be noticed that the investment cost is quite high. However, this is compensated by the higher environmental benefits, the lower payback time and the higher total annual savings [3].

5.2. China

a) In 1987, a solar-powered cooling and hot water system was designed, constructed and set in operation for a hotel in Shenzhen, Guangdong Province.

The system provided cooling in summer for a total area of 80 m^2 guestrooms, and supplied hot water to the hotel in other seasons. The system consisted of the following main components:

1. Solar collector system with three types of solar collectors: (*a*) Pass-through type evacuated tube collector (glass-to-metal sealed), aperture area 38 m^2, (*b*) Heat pipe vacuum tube collector (glass-to-metal sealed), 38 m^2, (*c*) Flat-plate collectors with *V*-corrugated insulating film, 41 m^2.
2. Two sets of single-stage LiBR absorption chillers with a cooling capacity of 7 kW each (WFC-600 Yazaki Co.).
3. Two 5 m^3 storage tanks for hot and chilled water.
4. Automatic control system: A control system was designed to decide when to start the first and the second chiller depending on the stored amount of heat and the trend of solar radiation, so that frequent switching on and off of the chillers could be avoided.
5. An automatic hot-water boiler was used as the auxiliary heat source [4].

As the first solar cooling demonstration project in China, the implementation of this project demonstrated technical successes and feasibility of solar cooling application in South China.

The chillers worked well within their specified limits of operation. On clear sunny days, the solar-powered system could provide cooling for guestrooms during the day- as well as night-time, early morning excepted. However, two main disadvantages existed which prevented the widespread practical use of such technology. One main problem was the economical aspect, as it required costly high-grade solar collectors to provide a generation temperature of about 90 ^{0}C in order to satisfy the strict driving temperature demand of the chiller. The other problem was that the chiller could not always operate at its nominal rating during periods of low solar radiation and high cooling water temperature because the temperature in the storage tank could not always be maintained at a temperature as high as 88-90 ^{0}C throughout the day even on clear sunny days [4].

b) During the late 1990s two large-scale demonstration projects of solar absorption cooling systems were built at: Jiangmen (Figure 5) and Rushan.

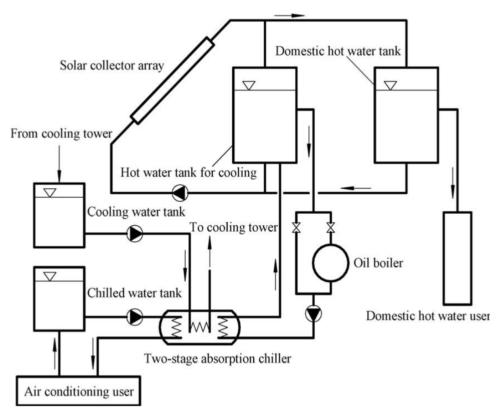

Fig. 5. *Schematic of integrated solar cooling and hot water system in Jiangmen* [4]

The main characteristics of the two systems are listed in Table 1. The building in Jiangmen was a 24-storey building, which consisted of hotels, business centers, entertainment places and an educational center. A solar system was installed on the roof of the building supplying hot water for daily use throughout the year and providing air conditioning for the educational center (located on the 22nd floor).

c) More recently two solar absorption cooling systems of Tianpu, see Figure 6, and Beiyuan were built in Beijing, which contributed to the concept of the green Olympics of 2008.

The main characteristics of the two systems are listed in Table 1.

During the last 20 years, solar cooling demonstration projects based either on absorption or adsorption were mainly applied in public buildings [4].

Nearly all solar cooling systems are multifunctional and were used to supply heating and hot water in other seasons. Solar-cooling technologies are still unsuitable to be spread on a large scale in residential buildings because of high initial cost and high specific collector area, i.e. installed solar collector area per unit of installed cooling capacity. As for public buildings, it is highly recommended to design solar-powered integrated energy systems. Owing to the fact that there is always enough roof area to install solar collectors, solar-powered integrated energy systems are capable of supplying cooling and heating, and even can enhance natural ventilation besides hot water supply. For the purpose of all-weather operation, it is necessary to install auxiliary heat sources to supplement solar-powered cooling systems. From demonstration projects, it is considered that highly efficient heat pumps, either ground-source or air-source equipments depending on the specific conditions, are perfect schemes to act as auxiliary heat sources. In China, it is thought that ground source heat pumps, GSHP, are suitable for North China areas; however, air-source heat pumps are fit for South China areas [4].

The main characteristics of the systems Table 1

Components	Jiangmen project	Rushan project	Tianpu project	Beiyuan project
Type of solar collector	Modified flat-plate collector	Heat pipe evacuated tubular collector	Heat pipe evacuated tubular solar collectors and U-type evacuated tubular solar collectors	Heat pipe evacuated tubular collector
Solar collector area	500 m^2	540 m^2	812 m^2	540 m^2
Type of chiller	Two-stage LiBr absorption chiller	Single-effect LiBr absorption chiller	Single-stage LiBr absorption chiller	Single-effect LiBr absorption chiller
Nominal cooling capacity	100 kW	100 kW	200 kW	360 kW
Hot water temperature	75°C	88 °C	75-90°C	83-88 °C
Chilled water temperature	9 °C	8°C	12-15 °C	8-11°C
Air conditioned area	600 m^2	1000 m^2	8000 m^2	3000 m^2
Auxiliary heat source	Oil boiler	Oil boiler	Ground-source heat pump	Electric boiler

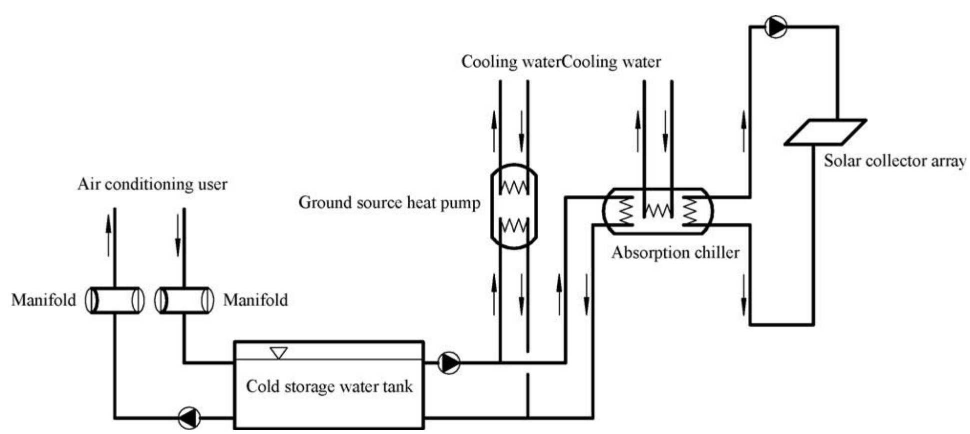

Fig. 6. *Schematic plan of solar cooling system in Tianpu* [4]

5.3. France

The solar cooling installation described below was conceived in France, for a continental climate, to cool 3700 m² offices area in an industrial building.

The absorption solar cooling system is operated by a 105 kW cooling capacity YAZAKI chiller supplied by 300 m² of evacuated tube collectors (i.e. 2,86 m²/kW specific collector area), shown in Figure 7.

Fig. 7. *Solar collector field* [8]

The system includes a 256 kW wet open cooling tower being assisted by a hot 400 kW back-up gas boiler and by a cold 211 kW gas-fired absorption plus a 200 kW compression chiller back-up [8].

Consequently, the solar cooling system represents only a part of the total heat and cold production system and the absorption chiller is thermally driven by two different energy sources: solar and fossil fuel.

From a TOTAL of 315,000 € (100%) the cost balance is as follows:

- collector 145,000 € (48%);
- auxiliary 47,400 € (18%);
- chiller 67,800 € (18%);
- back-up 39,750 € (11%) and
- control 15 200 € (5%).

This case study presents two particular features which are disadvantageous in terms of costs but partially due to the innovative system concept:

- First, the engineering costs are up to 100,000 €, because the overall system design is quite complex and the control system is an advanced one [8].
- On the other hand, the maintenance contract represents a high additional costs of 15,000 € per year because of sub-contracting, which should be avoided in a further project [8].

5.4. Italy

A demonstration project has been developed for the Mediterranean climate consisting of a ROTARTICA 4.5 kW cooling capacity absorption chiller, supplied by a 20 m² solar collector field (i.e. 4.4 m²/kW specific collector area), as shown in Figure 8.

Fig. 8. *Solar collector field* [8]

The design of the net collector area normalized to the installed chiller capacity is 4.4 m²/kW.

The absorption chiller is air-cooled, a technology possible thanks to its small capacity, which is a successful measure in order to reduce costs. There is no back-up system and no storage included in the system design, what implicates a lower investment cost [8].

The financial distribution is the following:

- collector 5573 € (19%);
- auxiliary 10 258 € (35%);
- chiller 9 535 € (32%);
- back-up & control 4,050 € (14%) [8].

5.5. Romania, Braşov

The installation used for research in the Building Services Department at *Transilvania* University of Brasov is able to cool and/or heat a 320 m² area of offices and classrooms. Working in a moderate continental climate the facility consists of a AYF 60-119/4 standard version chiller having a cooling capacity of 17.49 kW (at a nominal chilled water flow of 2735 L/h and a gas consumption of 2.51 m^3/h) and a GAHP-AR type heat pump with 35.2 kW heating capacity (for a thermal input of 25.2 kW), as shown in Figure 9 [7].

In its reversible operation mode the heat pump has a cooling capacity of 16.9 kW. For every 100 kW resulting from the natural gas burned inside the equipment the unit recuperates 54 kW from the ambient air. The resultant 144 kW heating capacity is accompanied with a flue loss of 10 kW [1].

For a gas consumption of 2.67 m^3/h and 0.9 kW of electricity the GAHP produces 35.3 kW heat and 16.9 kW cold. With the same amount of gas a regular boiler having an efficiency of 90% would produce only 22.7 kW heat i.e. 64%. An air conditioning 0.9 kW power supply split device can cover only 16% of the 16.9 kW cold provided by the absorption system [7].

Fig. 9. *The heat pump and the chiller platform*

Compared with the conventional air conditioning systems for heating and for cooling the absorption one operates with higher efficiency, having an immediate effect on costs and on environment [7].

The price of such systems is higher than the compression ones as a result of their complexity, see Figure 11, but the possibility of using the solar energy to drive them increases their attractiveness for a future with less fossil fuel consumption and lower CO_2 emissions.

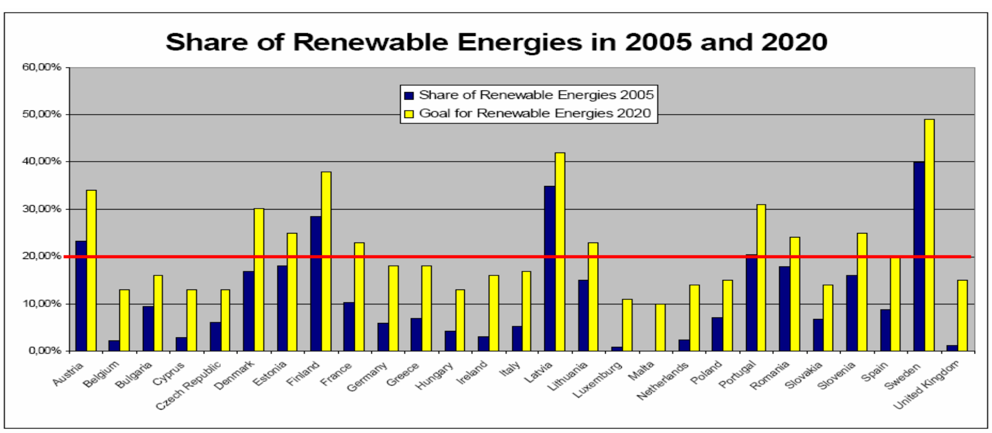

Fig. 10. *Solar collector field* [6]

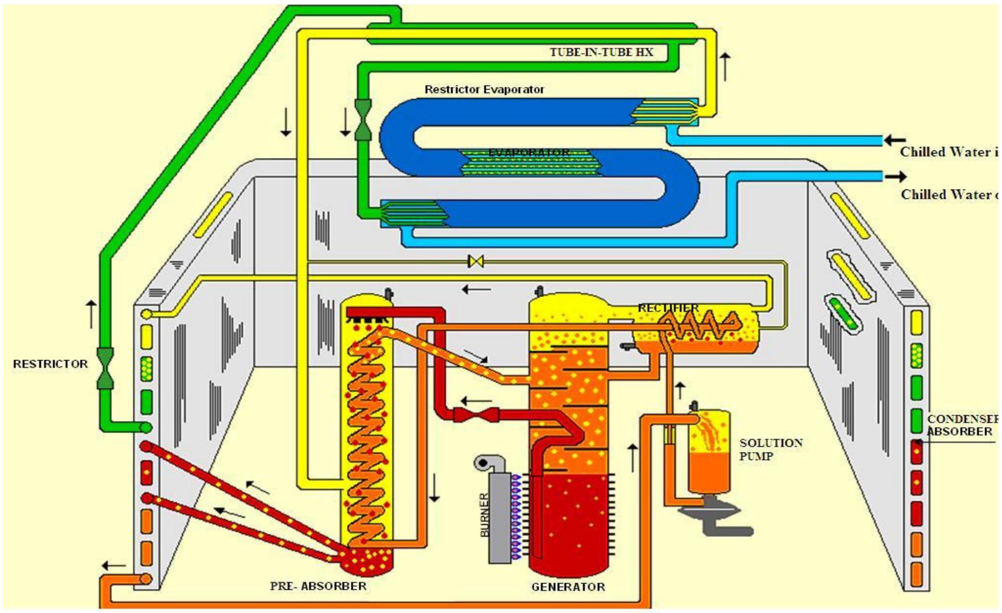

Fig. 11. *Schematic of the ammonia absorption system* [7]

6. Conclusions

The depletion of fossil fuels, the necessity to reduce the greenhouse gas (GHG) emissions (causing the global warming) and the European goal of covering 20% (Figure 10) of energy needs with renewable energy has resulted in considerable research focusing on alternative energy sources with special interest in renewable ones. Refrigeration and air conditioning based on absorption have been well known for more than a century. More recently systems based upon solar energy have been studied. Single-effect, indirectly driven lithium bromide air conditioning systems used for solar cooling, water or air cooled have been produced and commercialized in Japan, Spain and in the USA. However such systems have a higher initial cost due to the complexity of the equipment and the high quality collectors required. The demonstration projects realized in Europe (Greece, France, Spain, Italy, and Sweden) and in China and Mexico have proved the feasibility of solar cooling as a system but research is still necessary to gain information and experience in different conditions of operation.

Owing to the fact that there is always enough roof area to install solar collectors, solar-powered integrated energy systems are capable of supplying cooling, heating, and hot water supply. For the purpose of all-weather operation, it is necessary to install auxiliary heat sources to supplement solar-powered cooling systems.

The use of an absorption chiller during high summer-cooling demand periods or even in normal operating hours is economically beneficial especially in case of a favorable cost ratio of electricity to natural gas.

The main objective of the present study was to examine the feasibility of driving an absorption cooling unit with a low-temperature heat source.

The high initial cost of such systems makes them more suitable for public buildings rather than for residential ones.

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